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Review

Assessing Indirect Environmental Effects of Information and Communication Technology (ICT): A Systematic Literature Review

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Abstract: Indirect environmental effects of information and communication technology (ICT) are those effects of ICT that change patterns of production or consumption in domains other than ICT, or more precisely, the environmental consequences of these changes. Digitalization as the societal process of ICT-driven change has created increasing interest in the indirect environmental effects of this technology. Assessments of indirect effects face various methodological challenges, such as the definition of the system boundary, the definition of a baseline as a reference or the occurrence of rebound effects. Existing studies use various approaches or methods to assess a spectrum of ICT use cases in several application domains. In view of the large number of assessments that have been conducted, the choices made when applying assessment methods, and the variety of ICT use cases in different application domains investigated, we present a systematic literature review of existing assessments of indirect environmental effects of ICT. The review provides a state-of-the-art overview of the methods used in the research field and is intended to support researchers in designing sound assessments which yield significant results. We identified 54 studies in seven main application domains using 15 different assessment approaches. The most common application domains are virtual mobility (e.g., telecommuting), virtual goods (e.g., digital media), and smart transport (e.g., route optimization). Life-cycle assessment, partial footprint, and the "ICT enablement method" are the most common approaches. The major part of the assessments focuses on patterns of production (e.g., production of paper-based books vs. e-books), a smaller part on patterns of consumption (e.g., changes in media consumption). Based on these results, we identify as a research gap the investigation of ICT impacts on consumer behavior, which could, for example, focus on social practices, and account for the dynamic implications of change. Elaborating such an approach could provide valuable insights into ICT's impact on society and the resulting environmental consequences.

Keywords: information and communication technology; digitalization; indirect environmental effects; environmental impact assessment; greening through ICT

1. Introduction

Information and communication technology (ICT) has direct and indirect effects on the environment. Direct environmental effects of ICT include the resources used and emissions that are caused by the production, use, and disposal of ICT hardware. Indirect environmental effects of ICT are ICT-induced changes in patterns of consumption and production also in domains other than ICT and the environmental implications of these changes [1,2]. Both types of effects make ICT a relevant factor for the achievement of the United Nations (UN) Sustainable Development Goal (SDG) 12—"Responsible consumption and production" [3]. Studies assessing indirect effects often conclude that they are desirable from an environmental perspective (e.g., reducing greenhouse gas (GHG) emissions) and that they are in total clearly larger than the direct effects (e.g., leading to a net reduction of GHG emissions) [4–7].

To quantify these effects, researchers usually conduct some type of environmental impact assessment of indirect effects of ICT, which can be defined as "the process of identifying the environmental consequences of an ICT solution's capacity to change existing consumption and production patterns, taking into account the interrelated socio-economic, cultural, and human-health impacts, both beneficial and adverse, with the aim of informing decision-makers or the general public and mitigate unfavorable or promote favorable environmental consequences" [8] (p. 3).

Researchers from the "ICT for Sustainability" (ICT4S) community conducted environmental assessments of many ICT applications in various domains, while using different assessment methods. Due the large variety of ICT applications and assessment methods, it is difficult to compare these studies with each other. The methods face various challenges, such as the definition of the system boundary, the definition of the baseline used for comparison, the allocation of impacts to the ICT use case under study, or the estimation of rebound effects. These issues create degrees of freedom in the assessment methods, which lead to a high diversity of results, even for studies with similar research questions [4].

For example, the "SMARTer 2030" study by the Global e-Sustainability Initiative (GeSI), the ICT industry's association for sustainability, suggests that ICT applications could avoid up to 20% of annual GHG emissions in 2030 (indirect effect) on a global scale, while the ICT sector causes only 2% of global GHG emissions (direct effect) [6]. Similar results were reported before in GeSI's "SMARTer 2020" and "SMART 2020" study [9,10]. In contrast, a System Dynamics (SD) model developed in a project commissioned by the Institute for Prospective Technological Studies (IPTS) of the European Commission on "The Future impact of ICT on environmental sustainability" suggests that, by 2020, the positive and negative effects of ICT on GHG emissions tend to cancel each other out across application domains [11]. These diverging results can be explained by a difference in approaches: The IPTS study was based on a dynamic socio-economic model, whereas the newer studies used a static approach, which is based on a much simpler model [4].

In view of the large number of assessments which have been conducted, the choices made when applying assessment methods, and the variety of ICT application domains investigated, we provide a review of existing studies on indirect environmental effects of ICT. The aim of this review is not to summarize and compare the actual results of the assessments, but rather to provide a state-of-the-art overview of the methods that are applied in the research field to support future researchers in designing sound assessments, which yield significant results.

In that sense, we will provide an overview of existing assessments answering the following three research questions:

RQ1: What assessments of indirect environmental effects of ICT have already been conducted?
RQ2: What ICT applications have been assessed?
RQ3: What assessment methods have been used for the assessment of indirect environmental effects of ICT?

Several researchers have already conducted literature reviews in the field of assessing environmental effects of ICT. Verdecchia et al. [12] reviewed studies with regard to the types of environmental effects investigated (e.g., obsolescence effect, optimization effect). Yi and Thomas [13] conducted a literature review about assessments of the environmental impact of e-business, Klimova [14] on the use of knowledge management systems for "Green ICT" and "ICT for Greening", and Frehe and Teuteberg [15] on the role of ICT in the field of "Green Logistics". Penzenstadler et al. [16], Bozzelli et al. [17], Calero et al. [18], and Salam and Khan [19] all provided literature reviews focusing on sustainability in the field of software systems. Although not being within the scope of this article, we want to mention that Krumay and Brandtweiner [20], Grimm et al. [21], and Arushanyan et al. [22] reviewed the assessments of direct environmental effects of ICT.

For the purpose of this paper, the study by Horner et al. [23] is especially relevant. They provide an overview of ICT4S taxonomies, application domains, and assessments of indirect environmental effects of ICT and find that the overall net effect of ICT is still unknown and that "increased data collection, enhancing traditional modeling studies with sensitivity analysis, greater care in scoping, less confidence in characterizing aggregate impacts, more effort on understanding user behavior, and more contextual integration across the different levels of the effect taxonomy" would increase the quality of research in this field [23] (p. 1). They briefly mention the methods that are used in the assessments of indirect environmental effects of ICT, but without discussing their advantages and disadvantages in detail. This is the gap we intend to close with the present study.

2. Materials and Methods

We conducted a systematic literature review (SLR) to identify assessments of indirect environmental effects of ICT, according to the PRISMA framework and the guidelines for systematic literature reviews by Siddaway [24,25].

We started by identifying the main search terms based on our research questions: ICT; environment; assessment; assessment method; indirect environmental effects of ICT.

For all of the main search terms, we derived alternative search terms by finding synonyms (e.g., "ICT" or "IT"), related terms, singular and plural forms (e.g., "assessment method" or "assessment methods"), and broader or narrower terms (e.g., "environment" or "GHG emissions"). An overview of the search terms used in the systematic literature search is provided in Table 1. We then determined final search terms by combining main search terms and their alternatives (e.g., ("ICT" OR "information and communication technology" OR "IT") AND ("environment" OR "sustainability" OR "sustainable") AND ("assessment" OR "evaluation" OR "case study")).

Table 1. Main and alternative search terms for the structured literature search.

Main Term	Alternative Terms
Information and Communication Technology	ICT, information technology, IT, informatics
Environment	Sustainability, sustainable, environmental
Global warming potential *	Climate change, climate protection, global warming, GHG emissions, GHG, greenhouse gas emissions
Assessment	Evaluation, analysis, calculation, estimation, appraisal, case study
Assessment method	Method, approach, environmental assessment method, environmental impact analysis
Indirect environmental effects of ICT	Indirect effects, second order effects, greening through ICT, greening by ICT, green ICT, enabling effects
ICT for Sustainability **	ICT4S, Environmental Informatics, EnviroInfo

* We added "global warming potential" as one specific environmental impact category, because many assessments of indirect environmental effects of ICT focus on this impact category. ** We added the search term "ICT for Sustainability" and related terms because they refer to research communities focusing, among other topics, on environmental effects of ICT.

As suggested by Siddaway [25], we selected the most common scientific literature databases and platforms Web of Science, Scopus, Google Scholar, and Google for the search. We also reviewed the conference proceedings of the two major conferences in the field of environmental effects of ICT: The international conferences ICT4S (ICT for Sustainability, http://ict4s.org/; proceedings 2013–2016) and the conference series EnviroInfo (Environmental Informatics, http://www.enviroinfo.eu/; proceedings 2011–2017).

We created a spreadsheet to record the search queries and the identified publications and used the reference management software Zotero to store the bibliographical information.

Finally, we executed the search queries on the mentioned databases. For all of the queries, we screened a maximum of the first 100 results. An exception was made for conference proceedings, where we screened all the papers in the respective volumes. The screening included the following steps: For all publications whose title indicated that they contain an assessment of an indirect environmental effect of ICT, we read the abstract and created a record if the abstract confirmed the assumption, or dropped the publication otherwise. In cases where we recognized that a specific query provided irrelevant results, we stopped screening the search results.

After the systematic search, we added publications already known to the authors as well as relevant publications that were referenced by publications that were identified in the systematic search. In particular, the review by Horner et al. [23] references many studies which we included in our review. After reading all relevant publications, we dropped further 79 publications, because ICT, its environmental impact, or both were not treated as central aspects. Figure 1 provides the number of publications included and dropped in each step of the literature search.

Finally, we classified the identified studies according to four different criteria: (i) the ICT application domain covered; (ii) the number of ICT use cases assessed; (iii) whether the focus is on patterns of production (e.g., production of paper-based books vs. e-book readers) or consumption (e.g., changes in media consumption); and, (iv) the methodological approach applied. We describe these aspects in more detail in Section 3.

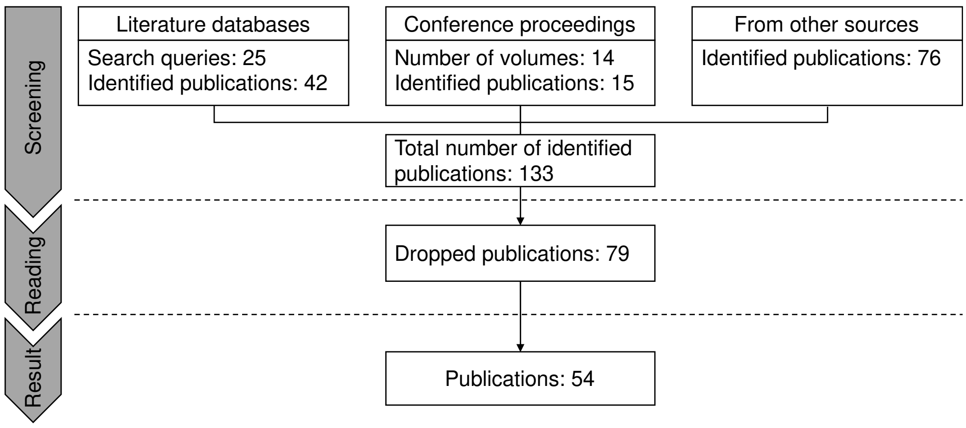

Figure 1. Number of search queries, volumes, identified and dropped publications in the screening phase (title and abstract), the reading phase (full text) and the final result.

3. Results

In the following, we present the results of our literature review, specifically (i) what application domains have been covered, (ii) the number of use cases focused on, (iii) whether the studies focused on ICT-induced patterns of production or consumption, and (iv) the methodological approaches applied.

Where suitable, we mention example studies for our results. Table 2 provides an overview of all studies that were finally identified. Figures 2 and 3 summarize the results of the literature review after applying the four criteria.

Table 2. Studies by application domain, number of use cases, production/consumption focus, and modeling approach. "Unspecified" means that the criterion is not applicable for this study.

Study	Application Domain(s)	Number of Use Cases	Production/ Consumption	Modeling Approach
[26]	All (macroeconomic study)	Unspecified	Both	Regression analysis
[6]	Shared goods, virtual mobility, smart transport, smart production, smart energy, smart buildings	12	Both	ICTem
[4,5]	Shared goods, virtual mobility, smart transport, smart production, smart energy, smart buildings	10	Both	ICTem
[27]	Smart energy	1	Both	Literature review/meta-analysis/scenarios
[28]	Smart energy, smart buildings	3	Unspecified	Literature review/meta-analysis
[29]	Smart production, smart buildings	4	Production	Descriptive statistics
[30]	Smart transport	1	Both	Transport model/partial footprint
[31]	Smart transport	1	Production	Vehicle drivetrain model/partial footprint
[32]	Smart transport	1	Production	Vehicle drivetrain model/partial footprint
[33]	Smart transport, smart production, smart buildings, others	>2	Not disclosed	ICTem
[34]	Virtual goods	1	Production	LCA
[35]	Virtual goods	1	Both	MIPS
[36]	Virtual goods	1	Both	LCA
[37]	Virtual goods	1	Both	LCA
[38]	Virtual goods	Unspecified	Both	Interviews/scenarios
[39]	Virtual goods	1	Production	LCA
[40]	Virtual goods	1	Production	LCA

Table 2. *Cont.*

Study	Application Domain(s)	Number of Use Cases	Production/ Consumption	Modeling Approach
[41]	Virtual goods	1	Production	LCA
[42]	Virtual goods	1	Production	LCA
[43]	Virtual goods	1	Production	LCA
[44]	Virtual goods, virtual mobility	2	Both	LCA
[45,46]	Virtual goods, virtual mobility, smart transport, smart production, smart energy	14	Both	ICTem
[47]	Virtual goods, shared goods, virtual mobility, smart transport, smart production	>8	Both	Scenarios/literature review
[48]	Virtual goods, virtual mobility, smart transport, smart energy, smart buildings	7	Not disclosed	Not disclosed
[49]	Virtual goods, shared goods, virtual mobility, smart transport, smart buildings	9	Both	ICTem
[50]	Virtual goods, virtual mobility, smart transport, smart production, smart energy, smart buildings	13	Both	ICTem
[9]	Virtual goods, virtual mobility, smart transport, smart production, smart energy, smart buildings	39	Both	ICTem
[51]	Virtual goods, virtual mobility, smart transport, smart energy, smart buildings	6	Not disclosed	Not disclosed
[52]	Virtual goods, shared goods, virtual mobility, smart transport, smart production	19	Both	ICTem
[11,53]	Virtual goods, shared goods, virtual mobility, smart transport, smart production, smart buildings	15	Both	System Dynamics
[54]	Virtual goods, shared goods, virtual mobility, smart transport, smart production, smart energy	9	Both	ICTem
[55]	Virtual goods, virtual mobility, smart transport, smart production, smart energy, smart buildings	17	Both	ICTem
[10]	Virtual goods, shared goods, virtual mobility, smart transport, smart production, smart energy, smart buildings	35	Both	ICTem
[56]	Virtual mobility	1	Both	Partial footprint
[57]	Virtual mobility	1	Consumption	Survey/interviews/partial footprint

Table 2. *Cont.*

Study	Application Domain(s)	Number of Use Cases	Production/ Consumption	Modeling Approach
[58]	Virtual mobility	1	Both	LCA
[59]	Virtual mobility	1	Both	Agent-based model/partial footprint
[60]	Virtual mobility	1	Both	Survey/partial footprint
[61]	Virtual mobility	1	Both	LCA
[62]	Virtual mobility	1	Both	Survey/partial footprint
[63]	Virtual mobility	1	Consumption	Survey/interviews
[64]	Virtual mobility	1	Production	Partial footprint
[65]	Virtual mobility	1	Both	LCA
[66]	Virtual mobility	1	Both	LCA/survey
[67]	Virtual mobility, smart transport	1	Both	Transport model/partial footprint
[68]	Virtual mobility, smart transport	1	Production	LCA
[69]	Virtual mobility, smart transport	1	Production	LCA
[70]	Virtual mobility, smart transport	1	Both	Transport model/partial footprint
[71]	Virtual mobility, smart transport	1	Both	Transport model/partial footprint
[72]	Virtual mobility, smart transport	1	Both	LCA
[7]	Virtual mobility, virtual goods	6	Both	ICTem
[73]	Virtual mobility, smart transport, smart energy, smart buildings	7	Both	ICTem
[74]	Virtual mobility, smart transport, smart energy, smart buildings	7	Both	ICTem
[75]	Unspecified	Unspecified	Consumption	Interviews

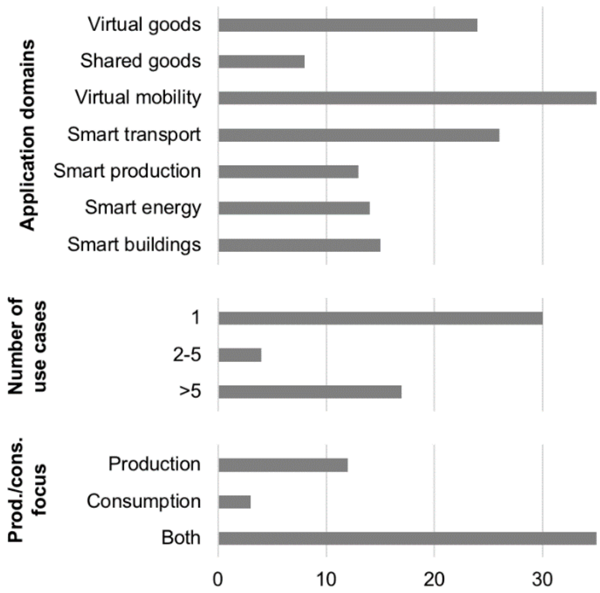

Figure 2. Number of studies by application domain, number of use cases, production vs. consumption focus. One study can cover more than one application domain.

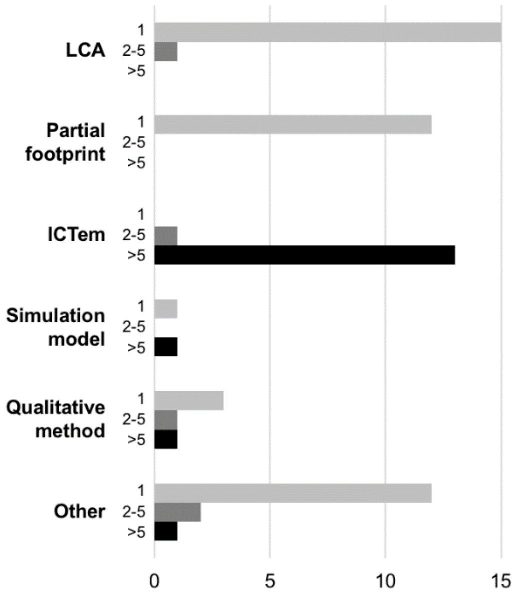

Figure 3. Number of studies by approach and number of use cases. Studies combining several methodological approaches were counted for each approach.

3.1. Application Domains

Assessments of indirect environmental effects of ICT address how and to what extent ICT as an enabling technology changes patterns of production and consumption in domains other than ICT. We classified all of the assessments according to the application domains they covered and derived a set of common application domains. Finding a collection of application domains that are extensive and mutually exclusive is challenging. For example, the domain *dematerialization*, as used by British Telecom (BT), refers to how ICT "replaces the need to manufacture, publish, print and ship newspapers, documents, books, CDs and DVDs for residential customers" [52] (p. 20), Hilty et al. use the term *virtual goods* to describe ICT's capacity to enable "a shift from material goods to services" [11] (p. 1262), whereas Coroama et al. [76] use the term *electronic media* to cover the transition from paper-based books to e-book readers and from physical travel to video conferencing. Producing and delivering a newspaper online instead of paper-based could be classified under all three mentioned domains; however, video conferencing would be a part of electronic media, as defined by Coroama et al. [76], but not part of dematerialization as defined by BT [52] or virtual goods as defined by Hilty et al. [11].

Despite these issues, we identified seven common application domains. These are mainly based on two well-cited studies of the overarching indirect environmental effects of ICT [6,11] and allowed for us to classify almost all other studies identified in the literature review (see Table 3). Most studies cover the application domains *virtual mobility*, *smart transport* and *virtual goods* (see Figure 2), followed by *smart buildings*, *smart energy*, *smart production*, and *shared goods*. Other application domains mentioned are *smart agriculture*, *smart water*, or *smart waste management*; however, these are less frequently assessed.

Two studies could not be classified with respect to application domains. Laitner et al. [26] conduct a regression analysis of historical macroeconomic time series data about the United Sates (U.S.) economy before and after the introduction of the semiconductor and thereby implicitly cover all potential application domains, without explicitly mentioning them. Røpke and Christensen [75] assess how ICT—in general—changes everyday life, also without focusing on specific application domains.

Table 3. Main application domains, descriptions and example use cases in the domain.

Application Domain	Description	Example Use Cases
Virtual goods	Replacing physical goods with ICT-based services	E-books, online newspapers, music and video streaming
Shared goods	Coordinating access to goods, increasing utilization	Sharing platforms
Virtual mobility	Replacing physical travel with ICT-based remote action	Video conferencing, e-commerce, e-health, distance learning, remote maintenance
Smart transport	ICT-enabled change of the process of transporting people or goods	Route optimization, traffic flow management
Smart production	ICT-enabled change of the processes and business models of production	Automation of production processes
Smart energy	ICT applications in the energy sector (mainly electricity supply)	Smart metering, demand side management, distributed power generation
Smart buildings	Change of building management enabled by ICT	Smart heating, smart lighting

3.2. Number of Use Cases

Most of the studies we identified assess specific ICT use cases (e.g., e-books, videoconferencing). Studies estimating the overall impact of ICT often select a number of the most common or prevalent use cases from various application domains and aggregate the environmental impacts across all use cases (e.g., [6,7,55]). We have to consider that the studies use different abstraction levels and definitions for use cases, which is why it is difficult to match the use cases across studies. Therefore, the numbers provided in the third column of Table 2 and in Figures 2 and 3 are to be interpreted with caution. From a methodological perspective, it is essential to distinguish between studies that are focusing on one use case only and studies investigating several use cases because in the latter case, interactions between use cases can (and should) be studied. Therefore, we distinguish between "single-use-case studies" and "multi-use-case studies" in the following.

In total, we found 30 "single-use-case studies" and 21 "multi-use-case studies". The latter usually apply relatively simple estimation methods to determine a specific environmental impact for each use case (e.g., GeSI applies the "ICT enablement method" (ICTem) in its SMARTer studies to estimate the ICT-induced GHG emission reduction potential for a collection of use cases [6,9,10,77]). There seems to be a trade-off between the depth of analyzing each use case vs. the scope of domains and use cases that are covered by the studies. Therefore, multi-use-case studies are often close to back-of-the-envelope calculations, also called "Fermi calculations", which try to derive a rough estimate from a few simple assumptions [78]. In contrast, the single-use-case studies usually apply methods allowing for a deeper analysis, including life cycle assessment or partial footprint (e.g., [39,40]). Mostly, the aim of these assessments is not just to estimate the environmental impact of the use case under study, but also to unveil the hidden mechanisms and impact patterns behind the use case in order to derive recommendations for policies or ICT application design. In search for deeper analysis, some studies also use simulation models. Xu et al. [59] create an agent-based model to investigate the impact of increasing Internet penetration on consumers' use of traditional and e-commerce book retailing schemes. Hilty et al. [11] apply System Dynamics modeling to investigate the impact of ICT on the energy, transport, goods, services, and waste domains, and how these impacts affect total energy consumption and GHG emissions.

Three studies have no focus on specific use cases. Picha Edwardsson [38] qualitatively explores the environmental impact of scenarios for future media use. As mentioned above, the studies by Laitner et al. [26] and Røpke and Christensen [75] could not be related to specific application domains.

3.3. Patterns of Production and Patterns of Consumption

ICT changes both the patterns of production (e.g., by changing manufacturing processes) and patterns of consumption (e.g., by changing individual media use). As can be expected, changes in production and consumption patterns are closely interrelated. For example, optimization of logistics has decreased the cost of logistic services (the service can be produced at a lower price and faster), such that e-commerce retailers can afford to offer free delivery and return to consumers, which dramatically changed consumer online shopping behavior (e.g., the online retailer Zalando had an order return rate of roughly 50% in 2013 [79]).

12 of the assessments identified in our literature review focused on ICT's impact on patterns of production. Moberg et al. [39], for example, compares the environmental impact associated with production, use, and disposal of paper-based books vs. e-books. Such studies commonly use product-oriented assessment methods, such as LCA or partial footprint.

35 assessments focusing on ICT's impact on patterns of production also consider changes in patterns of consumption. Many of these studies use ICTem. They first assess the impact of ICT on production processes and then the reaction of consumers to it. GeSI [6], for example, calculate the GHG emissions that are associated with the provisioning of ICT-based learning, health, and transport services, and then estimate how many consumers will adopt these solutions in future.

Only three assessments focus on ICT's impact on patterns of consumption exclusively. For example, Atkyns et al. [57] use survey results to assess employee telecommuting behavior, as well as drivers and challenges of telecommuting adoption, without assessing the actual environmental impact of telecommuting compared to conventional commuting. These studies use consumer-centric assessment methods to identify changes in individual consumption, such as interviews or surveys.

3.4. Methodological Approach

Researchers use a variety of approaches for the assessment of indirect environmental effects of ICT. The assessments identified in our literature review used 15 approaches, namely agent-based modeling (ABM), system dynamics (SD), life cycle assessment (LCA), partial footprint, the "ICT enablement method" (ICTem), regression analysis, descriptive statistics, material input per service unit (MIPS), transport models, vehicle drivetrain models, scenario analysis, literature review, meta-analysis, interviews, and surveys. LCA, ICTem, and partial footprint are by far the most frequently used assessment approaches, whereas simulation methods and qualitative approaches are less often applied. In the following we describe the approaches and how they are applied in the field of indirect environmental effects of ICT. We exclude descriptive statistics, interviews, surveys, vehicle drivetrain models, literature review, and meta-analysis, as these are too generic. We further add the Software Sustainability Assessment method (SoSa), a recent approach proposed in the ICT4S community to assess the environmental impact of software systems [80,81]. Figure 3 subsumes meta-analysis, scenarios, transport models, vehicle drivetrain models, regression analysis, descriptive statistics, surveys, and MIPS under "others". "Qualitative methods" include interviews and literature reviews.

Life cycle assessment (LCA) is used to estimate the environmental impact of a product system, evaluated with environmental indicators, by modeling all exchange of energy and matter between the product system and its environment [82]. There are different types of LCA, which we do not distinguish in this study. Finnveden et al. [83] provide an overview about recent developments in LCA. For indirect environmental effects of ICT, LCA typically compares the environmental impact of two product systems that differ with regard to ICT application. For example, Moberg et al. [39] compare the environmental impact of reading paper-based books and reading books using an e-book reader. By applying LCA, they find that the production of an e-book reader causes approximately the same amount of GHG emissions as the production of 30 to 40 average books.

Many authors in the field of indirect environmental effects of ICT focus their analysis on selected life cycle stages only. For example, in their analysis of telecommuting, Kitou and Horvath [56] evaluate the energy consumption of homes, offices, and ICT equipment, looking at their use phases only. A more comprehensive LCA would at least include the emissions that are caused by the production and disposal of the ICT equipment or other crucial assets. In line with ISO 14067, which specifies a "partial carbon footprint of a product" as the "sum of greenhouse gas emissions [. . .] and removals [. . .] of one or more selected process(es) [. . .] of a product system [. . .], expressed as CO_2 equivalents [. . .] and based on the relevant stages or processes within the life cycle [. . .]" [84] (p. 2), we call such approaches *partial footprints*, even if the environmental indicator is not GHG emissions. Such studies calculate the emissions or energy consumption for selected processes only, without applying a full life cycle approach.

Material input per service unit is a product-oriented assessment approach developed by Schmidt-Bleek [85] to measure the resource productivity of services. It calculates the natural resources required throughout the life cycle of a product per unit of service delivered.

System dynamics (SD) is "a method that permits researchers to decompose a complex social or behavioral system into its constituent components and then integrate them into a whole that can be easily visualized and simulated" [86] (p. 3). The interaction among system elements is modeled by connecting stocks with material flows, such as water running through pipes (flow) and increasing the water level in a bathtub (stock), and stocks and material flows with information flows [86]. The key strengths of SD are that it helps decomposing complex systems into causally connected variables and that it can be executed by computer simulation to observe the behavior of the system over time. It is for these strengths that SD is often used in policy analysis. In the literature review, we found only one application of SD. Hilty et al. [11] used SD to simulate the impact of ICT on environmental sustainability in the year 2020 (starting in the year 2000) in order to evaluate policy scenarios.

In *agent-based modeling (ABM)*, a system "is modeled as a collection of autonomous decision-making entities called agents. Each agent individually assesses its situation and makes decisions on the basis of a set of rules" [87] (p. 1). In a simulation experiment, agents repeatedly interact with each other and with their environment. Their collective action determines the behavior of the system as a whole [87]. ABM is especially useful to study emergent phenomena, e.g., macroeconomic phenomena emerging out of behavior at the micro level [88]. Xu et al. [59] use ABM to test different e-commerce book retailing schemes, the reaction of consumers to it, and how these affect the CO_2 emissions that are associated with book retailing.

Scenarios "denote both descriptions of possible future states and descriptions of developments" [89] (p. 723). *Scenario analysis* is a method in the area of future studies. Future studies are a collection of methods to "explore possible, probable and/or preferable futures" [89] (p. 724). Comparing different scenarios that are based on different assumptions about future ICT development can provide insights on the environmental consequences of ICT application. Arushanyan et al. [90] use scenario analysis in combination with LCA and develop a framework specifically for the environmental and social assessment of future ICT scenarios.

The *ICT enablement method (ICTem)*, as introduced by GeSI in 2010 [77], can be used to quantify the carbon-reducing effect of ICT use cases. ICTem is useful to quickly provide a rough estimate of the environmental impact of an ICT solution. The approach is close to a Fermi problem or "back-of-the-envelope calculation". In the SMART 2020, SMARTer 2020 and SMARTer 2030 reports [6,9,10], GeSI uses ICTem by

- identifying GHG abatement levers (e.g., reduction in transport demand),
- estimating baseline emissions,
- estimating the level of adoption of the use cases in the population,
- estimating the impact on GHG emissions per unit of adoption, and
- estimating the rebound effect (for an example see Figure 4).

A feature that distinguishes ICTem from a partial footprint is that ICTem focuses on the mechanisms that cause the changes of environmental impact. Such studies almost exclusively present favorable indirect environmental effects of ICT, even though the method would also allow for estimating the size of unfavorable effects (e.g., by including induction effects or obsolescence effects [1]).

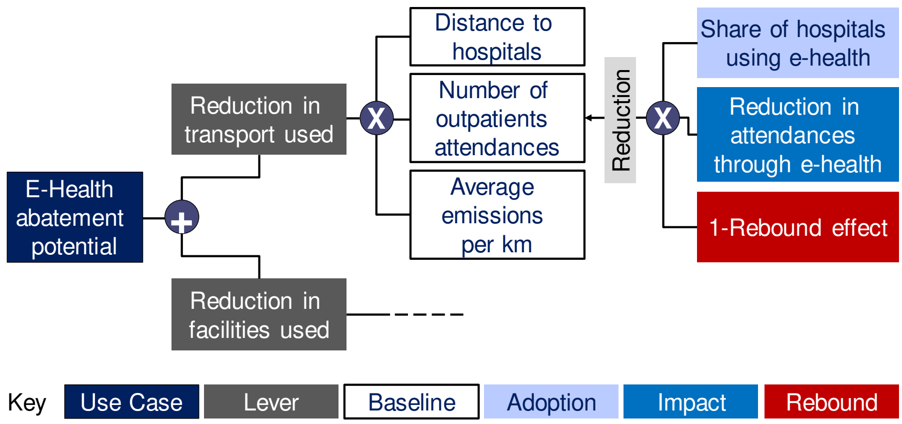

Figure 4. "ICT enablement" method used in the SMARTer 2030 study [6] (cited from [4]).

Studies that are focusing on the transport domain usually develop a *transport model* and assess how ICT changes transport. Transport models are usually combined with a partial footprint approach. Siikavirta et al. [71], for example, model the impact of different e-commerce schemes on road truck delivery and estimate the avoided fuel consumption and resulting GHG emissions.

Using *linear regression analysis* [91], Laitner et al. [26] estimate how the relationship between energy consumption (dependent variable) and economic growth and semiconductor investment (independent variables) in the U.S. changed after the introduction of semiconductor technologies. The application of regression analysis for indirect environmental effects of ICT can be manifold, for macroeconomic effects (see Laitner et al. [26]) or for specific ICT applications (e.g., the effect of a traffic management system on the concentration of particulate matter in a city). However, it always treats the assumed causal mechanism as a black box and it does not reveal underlying system structures.

Even though we could not find application examples, we would like to mention the *software sustainability assessment (SoSa)* method, a recent approach to assess the environmental impact of software systems. SoSa analyzes the immediate, enabling, and systemic impacts of software systems on "economic, social, environmental and technical" sustainability [80] (p. 1). The result is similar to a causal loop diagram and helps to understand the relevant impacts of a software system to improve software design [80,81].

4. Discussion

4.1. Applied Methods and Number of Use Cases

A comparison of methodological approaches is challenged by the variety of the purposes of the existing studies. For example, ICTem is useful for rough comparative assessments of ICT application domains and use cases. A study about the GHG abatement potential of ICT in Switzerland showed, for example, that the highest potentials to avoid GHG emissions through ICT can be found in the transportation, buildings, and energy domains [5,92]. However, such studies also face several methodological challenges, such as the definition of system boundaries, interaction among use cases, or rebound effects, which have to be carefully considered to judge the significance and comparability of results [4]. More detail-oriented methods, such as LCA or a partial footprint, are more useful to assess the inherent complexities of specific ICT use cases in order to improve the design of an ICT solution or derive policies to mitigate unfavorable environmental impacts or promote favorable environmental impacts at the product level. Dynamic simulation methods, such as ABM or SD, are also useful to develop such policies. While SD is most useful for describing causal mechanisms at the socio-economic macro-level analysis, ABM is useful to explain macro-level phenomena with micro-level behavior.

4.2. Dynamic System Modeling as an Exceptional Case

As Ahamadi Achachlouei [93] points out, assessments of indirect environmental effects of ICT can either rely on dynamic or on static (steady-state) models. He performed different assessment studies using LCA, SD, and ABM, and recommends "employing an LCA method" (static) to assess "direct environmental effects of ICT production, use, and disposal" or indirect effects by comparing LCAs of "ICT applications with conventional alternatives" (p. 58). He also suggests using "system modeling methods" to "describe the drivers of change, as well as the dynamics of complex social, technical, and environmental systems that are associated with ICT applications" (p. 58).

In our study sample, most of the studies use LCA or similar static approaches to compare the environmental impact of a baseline product system or baseline scenario (representing a situation *without* the adoption of a given ICT use case) with a system or scenario *with* the adoption of an ICT use case (e.g., [39,40,62]). Only two studies use dynamic system modeling approaches—SD and ABM. By conducting simulation experiments with dynamic models, Hilty et al. [11] and Xu et al. [59] reveal causal mechanisms linking interventions (represented by changes in initial conditions and settings of model parameters) to environmental effects.

4.3. Consumption Side Is Underexplored

Many assessments investigate how ICT changes patterns of production using a product-oriented modeling approach, such as LCA or partial footprint. Focusing on production is useful to understand the environmental consequences of (roughly) functionally equivalent product systems, with and without the application of ICT. A change in production behavior (e.g., people will read e-books instead of printed books), is treated as an exogenous variable. Focusing on consumption means to treat the demand levels for the several types of goods or services under study as endogenous variables. This is necessary if the study wants to show how ICT changes individual or collective consumption patterns.

Only three studies [57,63,75] focus exclusively on consumption patterns in the above sense. Such studies use consumer-centric assessment methods, such as interviews or surveys to interrogate consumers about their consumption behavior and potential changes. Environmental consequences are then estimated by comparing the environmental impact of the goods and services that are consumed by individuals before and after the ICT-induced change.

Practice theory can be used as a lens to investigate consumption. As opposed to other social science theories, which focus on individual attitudes, values, and beliefs, social practice theory focuses on "social practices ordered across space and time" [94] (p. 2) [95]. For example, Røpke and Christensen [75] assess how ICT changes the activities that are performed by individuals throughout one day and the energy consumption that is associated with these activities. They show that applying a social practice perspective can provide valuable insights into ICT's impact on society and the environmental consequences.

5. Limitations

A limitation of this SLR is that we probably could not identify all relevant assessments of indirect environmental effects of ICT that exist in literature, or were biased by our personal background and opinions when manually including or excluding studies. These are limitations that SLRs face in general. We tried to minimize the risk of distorted results by deriving only robust results. As Mallet et al. [96] (p. 453) put it, SLR, should be seen as "helping to get a robust and sensible answer to a focused research question".

6. Conclusions and Outlook

We searched common scientific literature platforms and conference proceedings for studies assessing indirect environmental effects of ICT. We identified 54 studies assessing indirect environmental effects of ICT, in seven main application domains, using 15 different methodological approaches. The most common application domains are virtual mobility (e.g., telecommuting), virtual goods (e.g., digital media), and smart transport (e.g., route optimization). LCA, partial footprint, and ICTem are the most common methodological approaches. LCA and partial footprint are commonly used in single-use-case studies to investigate the relative change that is induced by a specific way of applying ICT. ICTem is commonly used in multiple-use-case studies and it is sometimes used with the ambition to estimate and compare the environmental impact of digitalization in the large. Dynamic system models are less frequently used, but have shown to help explore the causal mechanisms behind ICT-induced change in socio-economic systems, including rebound effects.

More assessments focus on production rather than on consumption patterns. Both perspectives are required to fully understand how ICT changes economic processes and indirectly their environmental impact—what goods and services people consume, how they are produced, and how the product systems interact with the environment.

Some studies addressed the question how ICT changes social practices. Understanding how ICT changes consumer behavior, e.g., by analyzing activities of individuals, seems to be an underexplored, but essential aspect of the causal mechanisms that have to be understood for predicting the environmental impact of digitalization. Future research should close this gap by paying more attention to ICT-induced changes in social practices and related consumption patterns. In a digital society, this type of research could become instrumental for the achievement of the UN Sustainable Development Goal 12—Responsible consumption and production.

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